THE CHEMICAL EVOLUTION OF THE MILKY WAY

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1. Introduction

The field of chemical evolution modeling of the Galaxy is experiencing in the last years a phase of high activity and important achievements. There are, however, several open questions which still need to be answered. In this review I will try to summarize what have been the most important achievements and what are some of the most urgent questions to be answered.

The reason for the recent increase of activity and success of chemical evolution models is probably two-folding. First of all, on the observational side, the last decade has witnessed a tremendous improvement in the quality and in the amount of data on the major Galactic features, like the chemical abundances and abundance ratios in stellar and gaseous objects of various types, the density distributions of gas and stars in different Galactic regions, etc.: Fundamental data which provide stringent constraints on evolution models. In addition, also on the theoretical side there has been a recent blooming of new studies, with several new groups working on stellar nucleosynthesis to derive reasonable yields for stars of all mass and of several initial metallicities, and taking into account as much as possible the large uncertainties affecting the latest evolutionary phases. If we consider that for almost two decades the only usable set of yields for low and intermediate mass stars was that provided by Renzini & Voli (1981), while now we can choose among those by Forestini & Charbonnel (1997), van den Hoek & Groenewegen (1997), Boothroyd & Sackman (1998) and Marigo (1998 and this volume), all published in the last two years, it is apparent that we have entered an era of great interest in stellar nucleosynthesis studies.

These circumstances have favoured the appearance in the literature of an increasing number of good chemical evolution models computed by an increasing number of people. Nowadays there are several models able to

satisfactorily reproduce all the major observational constraints, not only in the solar neighbourhood but also in the whole Galaxy. Only in the last few months one could count at least four different groups who have presented models in fairly good agreement with the data: Boissier & Prantzos (1999, hereinafter BP), Chang et al. (1999), Chiappini et al. (1999, CMP) and Portinari & Chiosi (1999, PC).

2. Major Results

Before analysing the various results, it is important to recall that standard chemical evolution models follow the large-scale, long-term phenomena and can therefore reproduce only the average trends, not the cloud-to-cloud, star-to-star fluctuations. To put it in Steve Shore's words: *They are a way to study the climate, not the weather, in galaxies.* This can be considered a limitation of the models, but is the obvious price to pay to avoid introducing too many free parameters that would make it much more difficult to infer the overall evolutionary scenario with sufficient reliability. As well known, we have not yet been able to find a unique scenario for the most probable evolution of the Milky Way (see e.g. Tosi 1988a), but we are converging toward a fairly limited range of possibilities for the involved parameters (initial mass function, IMF, star formation rate, SFR, gas flows in and out of the Galaxy).

Thanks to the improvements both on the observational and on the theoretical sides, good chemical evolution models of the Milky Way nowadays can reproduce the following list of observed features:

- Current distribution with Galactocentric distance of the SFR (e.g. as compiled by Lacey & Fall 1985);
- current distribution with Galactocentric distance of the gas density (see e.g. Tosi, 1996, BP and references therein);
- current distribution with Galactocentric distance of the star density (see e.g. Tosi, 1996, BP and references therein);
- current distribution with Galactocentric distance of element abundances as derived from HII regions and from B-stars (e.g. Shaver et al. 1983, Smartt & Rollerston 1997);
- distribution with Galactocentric distance of element abundances at slightly older epochs, as derived from PNe II (e.g. Pasquali & Perinotto 1993, Maciel & Chiappini 1994, Maciel & Köppen 1994);
- age-metallicity relation not only in the solar neighbourhood but also at other distances from the center (e.g. Edvardsson et al. 1993);
- metallicity distribution of G-dwarfs in the solar neighbourhood (e.g. Rocha-Pinto & Maciel 1996);

– local Present-Day-Mass-Function (PDMF, e.g. Scalo 1986, Kroupa et al. 1993);
– relative abundance ratios (e.g. [O/Fe] vs [Fe/H]) in disk and halo stars (e.g. Barbuy 1988, Edvardsson et al. 1993, Israelian et al. this volume).

As mentioned above, the most recent examples of how good models can fit the above list of observed Galactic features are given by BP, Chang et al. (1999), CMP and PC (see also in this book the contributions by Chiappini, by Portinari and by Prantzos).

If one bears in mind that the free parameters involved in the computation of standard chemical evolution models are essentially the IMF, the law for the SFR, and those for gas flows in and out of the Galaxy, it is clear that the number of observational constraints is finally sufficient to put significant limits on the parameters. In fact, if we compare the results of all the models in better agreement with the largest set of empirical data, we see that they roughly agree on the selection of the values for the major parameters. The conclusions that can be drawn from such comparison are:
• **IMF**: after several sophisticated attempts (e.g. CMP) to test if a variable IMF could better fit the data, it is found, instead, that a roughly constant IMF is most likely, even if the exact slopes and mass ends are still subject of debate.
• **SFR**: it cannot be simply and linearly dependent only on the gas density; a dependence on the Galactocentric distance is necessary, either implicit (e.g. through the total mass density as in Tosi 1988a or in Matteucci & François 1989) or explicit (e.g. as in BP). We don't know however what is its actual behaviour (see e.g. Portinari, this volume) or even if it should be considered as fairly continuous or significantly intermittent as recently suggested by Rocha-Pinto et al. (1999).
• **gas flows**: all the models in better agreement with the data invoke no or negligible galactic winds and a substantial amount of infall of metal poor gas (not necessarily primordial, e.g. Tosi 1988b, Matteucci & François 1989) and there are increasing observational evidences on this phenomenon (see also Burton, this volume). We have no empirical information, however, on the spatial and temporal distribution of the accretion process: uniform or not ? continuous or occurring in one, two or several episodes ? (e.g. Beers & Sommer-Larsen 1995, Chiappini et al. 1997, Chang et al. 1999).

3. Open Questions

It is apparent from the summary presented above that, in spite of the wealth of good data and models described in the previous sections, the scenario of the Milky Way evolution is not completely clear. There are still several issues we don't understand, including some of conspicuous im-

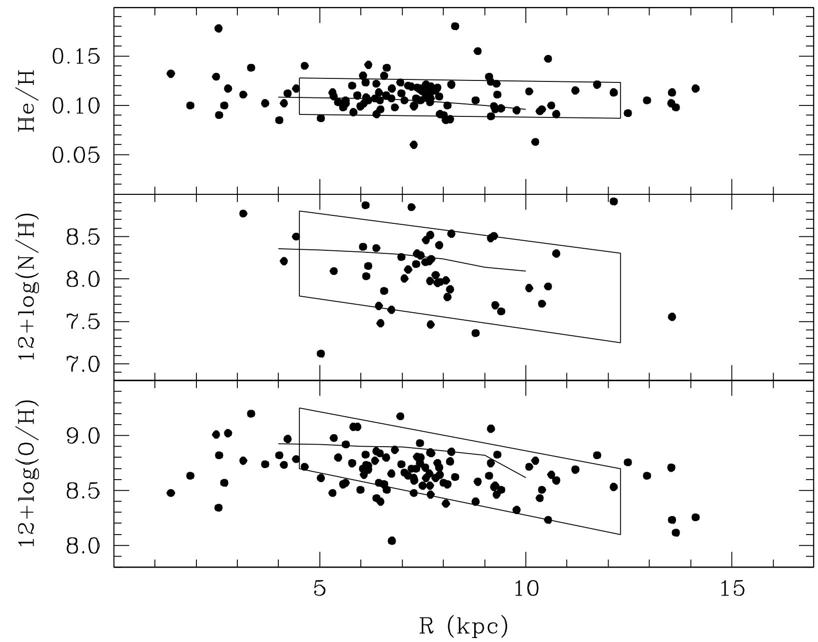

Figure 1. Radial distribution of the He, N and O abundances as derived from observations of PNe of type II (see text for references) and from the predictions of Tosi's (1988a) model 1 for the Galaxy medium 2 Gyr ago.

portance. Among these, I consider of special interest the evolution of the abundance gradients and that of CNO isotopes.

3.1. ABUNDANCE GRADIENTS

Thanks to the recent results by Smartt & Rollerstone (1997) we finally know that young objects (HII regions and B-stars) all show the same metallicity distribution with Galactocentric distance and a fairly steep negative gradient. All the models in better agreement with the Galaxy constraints are able to reproduce this distribution (see Tosi 1996, Chiappini, Portinari and Prantzos in this volume).

Slightly older objects, such as PNe of type II whose progenitors on average are 2 Gyr old, show similar abundances and possibly flatter gradients (e.g. Maciel & Köppen 1994). Good models of Galaxy evolution reproduce well not only the present abundance distribution, but also the distributions derived from PNeII observations. For instance, Fig.1 shows the predictions of the best of models of type 1 in Tosi's (1988a) set for the He, N and O abundance distributions with Galactic radius 2 Gyr ago. The adopted

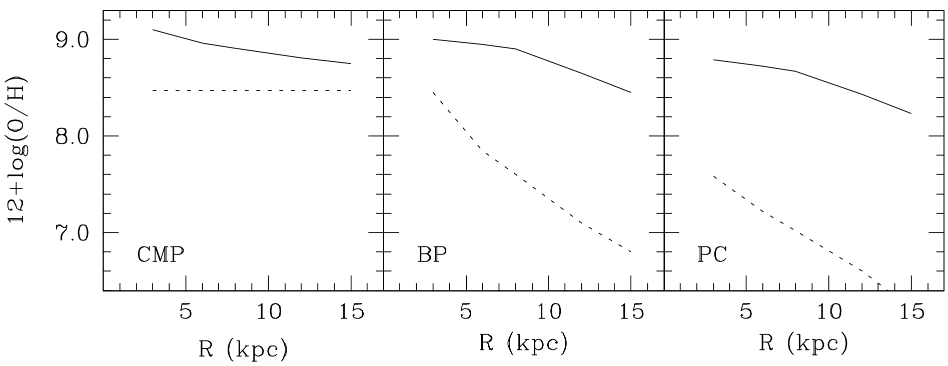

Figure 2. Oxygen gradients predicted by the models from Chiappini et al. (1999, left), Boissier & Prantzos (1999, center), and Portinari & Chiosi (1999, right). The solid curves refer to the present epoch and the dotted ones to 1 Gyr after the disk formation.

stellar yields are Marigo's (1998 and this volume) for low and intermediate mass stars and Limongi et al. (this volume) for massive stars. The data points correspond to the PNeII measures by Pasquali & Perinotto (1993) and the open boxes sketch the distribution of the values derived by Maciel & Chiappini (1994) and Maciel & Köppen (1994). The data sets are in perfect agreement with each-other and the model predictions fit well their average distributions.

When we consider earlier epochs, the predictions from different models diverge, despite the common assumption that the Galaxy is initially formed of primordial gas. For instance, the three models which are presented in this volume by Chiappini, Portinari and Prantzos, and that are in fairly good agreement with all the observational constraints, predict the gradient evolutions schematically described in Fig.2 (see BP, CMP and PC for more details). The initial distribution of oxygen with galactic radius in the left panel is totally flat, becomes initially slightly positive, then turns to negative and steepens with time, reaching at the present epoch the observed slope of -0.08 dex/kpc; vice versa, the gradient at 1 Gyr in the central panel is negative and quite steep and then slowly flattens with time, particularly in the inner galactic regions, reaching finally the observed slope at the present time; the same trend occurs in the right panel, but with different absolute abundances. If one compares (e.g. Tosi 1996) all the models able to reproduce the observed Galactic features, it is easy to understand that they present all the possible varieties of gradient evolution: from slopes initially positive becoming first flat and then increasingly negative, to slopes initially flat and then becoming increasingly negative, to slopes initially

negative and then becoming increasingly flat.

The reason for such a variety of gradient evolutions is the strong dependence of the radial slope on the radial variations of the ratio between ISM enrichment from stars (i.e. SFR) and ISM dilution from metal poor gas (i.e. initial conditions and/or infall of metal poor gas). Regions with higher SFR have larger enrichment, but can remain relatively metal poor if they contain or accrete large amounts of metal poor gas. It is then sufficient to have different initial conditions or different assumptions on the temporal behaviours of the SFR and of the infall rate to obtain quite different abundance gradients at the various epochs.

The following few examples of possible scenarios give an idea of the sensitivity of the gradient evolution to the boundary conditions:

- If the efficiency in the chemical enrichment of the inner Galactic regions at early epochs is low (for instance because the SFR is low and/or there is a high amount of primordial gas), then the early radial distribution of the heavy elements is flat. And to reach the observed present slope it has to become negative and steepen with time.
- If, instead, the enrichment efficiency in the inner regions at early epochs is high (for high SFR or low gas mass), then the early gradient is negative and steep. And to reach the present slope it has to flatten with time.
- If at late epochs the acretion (infall) of metal poor gas is stronger in the outer than in the inner regions, then the gradient tends to steepen with time because of the increasing dilution for increasing galactocentric distance.
- If at late epochs the inner regions exhaust their gas, then the metallicity saturates there and the inner gradient becomes increasingly flat with time.

All these scenarios are plausible: how can we understand which are the right ones ? If we knew the right history of the abundance gradients we would also know what is the most likely evolution of the Galactic disk. Unfortunately, despite their accuracy, the observational data already available on open clusters and on field stars are not yet sufficient to clearly distinguish whether the abundance gradients were steeper or flatter at early epochs. Open clusters are probably the best candidates to provide such information, thanks to their visibility at large distances and to the relative ease to derive their age and metallicity, but as described by Bragaglia (this volume, and references therein) the number of clusters treated homogeneously is still too small.

3.2. EVOLUTION OF CNO ISOTOPES

The CNO isotopes are important because they are stable, diffused and largely studied, since they provide the seeds for the production of heavier elements. In particular, the stellar nucleosynthesis of the carbon and oxygen isotopes is examined in detail in most of the most recent studies. Nonetheless, it is not completely clear yet how they should behave during the Galaxy evolution. The problem was already pointed out twenty years ago by Penzias (1980), who noticed that the observed decrease of the local $^{18}O/^{17}O$ from the solar to the local ISM value and the corresponding increase of $^{16}O/^{18}O$ were difficult to interpret. In fact, chemical evolution models predicted (Tosi 1982) $^{18}O/^{17}O$ to remain roughly constant in the last 4.5 Gyr and $^{16}O/^{18}O$ to steadily decrease. Those predictions were based on simple arguments on the relative enrichment of primary and secondary elements produced by stars of different masses, and have been confirmed by subsequent studies based on nucleosynthesis studies of solar metallicity stars (e.g. Prantzos et al. 1996).

These results for the carbon and oxygen isotopic ratios are represented by the solid line in Fig.3. The left hand panels show the time behaviour of the isotopic ratio in the solar neighbourhood as predicted by models and as observed in the sun and in the local ISM, which are assumed to be representative of the average local ratios 4.5 Gyr ago and now, respectively. The right hand panels show the present distribution with Galactocentric distance as predicted by the same models and as derived from radio observations of molecular clouds. The solid line corresponds to the same model presented in Fig.1 (Tosi-1), assuming the yields for solar initial metallicity computed by Boothroyd & Sackman (1998), by Forestini & Charbonnel (1997) and by Woosley & Weaver (1995) for low, intermediate and high mass stars, respectively. Qualitatively similar results were obtained by Prantzos et al. (1996) adopting the solar yields by Marigo et al. (1996), Renzini & Voli (1981) and Woosley & Weaver (1995). It is apparent that while the predictions for $^{12}C/^{13}C$ and $^{16}O/^{17}O$ are in fair agreement with the data, the time behaviour of the oxygen isotopic ratios involving ^{18}O is inconsistent with them. There have been several speculations on how this impasse could be overcome, with suggestions that either the theory or the data or both might be wrong or misinterpreted (see e.g. Prantzos et al. 1996, Tosi 1996, Wielen & Wilson 1998), but no solution has been found yet.

One possibility is that it is not correct to adopt solar yields also for the earlier epochs, when stars were certainly metal poorer. Now that stellar yields are available also for lower metallicities, we expect to find an improvement in the comparison between model predictions and observed

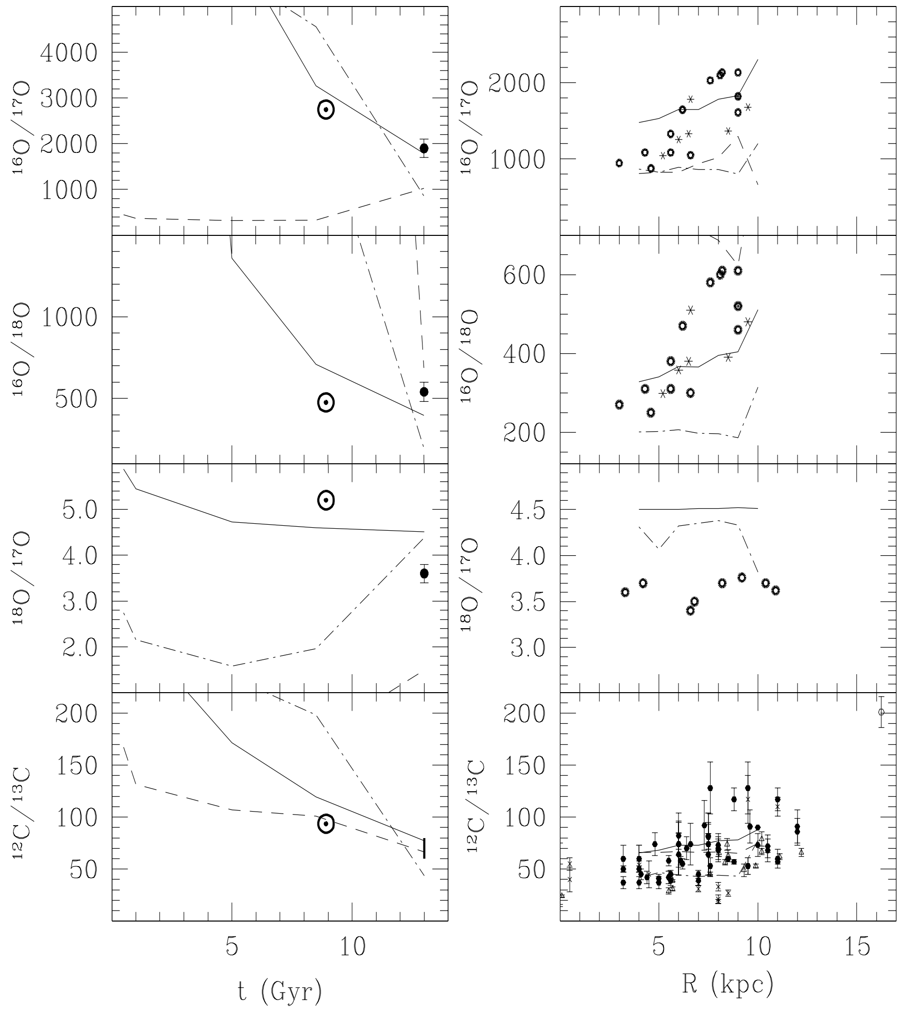

Figure 3. Carbon (bottom panels) and oxygen (three top panels) isotopic ratios. Left panels: evolution in the solar neighbourhood. Right panels: current distributions with Galactocentric distance. The solar symbol represents the solar ratio derived from Anders & Grevesse 1989; all the other data are from radio observations of molecular clouds (see Sandrelli et al. 1998, for references). All the curves refer to Tosi (1988a) model 1 but assuming different stellar yields as described in the text.

ratios. Unfortunately, this is definitely not the case, as clearly shown by the dashed and dash-dotted lines in Fig.3. The dash-dotted curve represents the same model as the solid curve, with the same sources for the yields, but adopting the low metallicity yields at earlier epochs and the solar ones only when the ISM reaches Z=0.02. It is apparent that, rather than improving the agreement with the data, this curve worsens the fit, both for the lo-

cal evolution and for the current distribution with Galactocentric distance. This result is strongly dependent on the adopted yields and we may hope that different nucleosynthesis studies would provide more consistent predictions, but so far no set of stellar yields is able to reproduce all the shown observed distributions. Some of the available yields do improve the results on one isotopic ratio, but worsen the results on other ratios, as exemplified by the dashed lines, showing the predictions of the same model when Marigo's (this volume) metallicity dependent yields are adopted for low and intermediate mass stars and Limongi's et al. (this volume) for massive stars: the data on the carbon isotopic ratio are now well reproduced, but the predicted oxygen ratios are definitely inconsistent with the data.

I will then conclude this short description of the state of the art in Galactic chemical evolution models by emphasizing that, despite the great work that has been done by observers and theoreticians to improve the number and the quality of the observational and theoretical constraints, further efforts on both sides are needed to shed light on several unclear issues. In particular, it would be important to derive accurate chemical abundances in stars and clusters of different ages and Galactic locations and to study in better detail the stellar nucleosynthesis in stars of all masses and initial metallicities.

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